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SR06 Small Racetrack Magnet Test Summary

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Content:

1. Introduction

Small racetrack (SR) coil magnet SR06 was built at Fermilab using 27-strand Rutherford (keystoned) cable made of 1 mm diameter Nb_3Sn strand. Strands based on the Restack Rod Process (RRP) of 114/127 design were developed and produced by Oxford Superconducting Technologies, Inc. (OST) [1]. Cable for SR06 magnet (HFDB_070531_27_1_0) was manufactured at Fermilab using strands with the billet number of 9772-1. The witness samples were tested at the Fermilab short sample test facility to estimate the SR06 coil short sample limit (see Appendix I). Previously the SR03 magnet made of 1 mm Nb_3Sn RRP strand of 108/127 stack design was built and successfully tested at Fermilab [2],[3]. SR03 reached its short sample limits at 4.5 K producing a field of 11 T [3].

The SR06 magnet was delivered to the Fermilab magnet test facility at the beginning of March and it was electrically checked by March 12th. Due to the water leaking problem in the 30 kA power supply SR06 cold test was started only on March 18th. Test was interrupted again from March 21 to March 31 due to another problem with the power supply - the hand breaker failure in one of the PEI power supply modules. The cold test was completed on April 5th. Warm up was started on the same day, but the magnet was left in the VMTF dewar until April 21st because of the maintenance shutdown of the refrigerator plant.

The Voltage Spike Detection System (VSDS) was used for detection of small magnetic flux changes in the magnet. Results of the SR06 spike data analyses, as well as of the magnet mechanical analyses, will be presented in a separate note.

2. Instrumentation

The total length of the cable in the SR06 magnet was up to 14 m. Two racetrack coils are wound in opposite direction with the 2 mm gap between them. There are 12 turns of cable per layer.

Voltage tap system covers both coil layers. There are voltage taps before and after the splice at each lead, a voltage tap between the two layers and 2 voltage taps on each layer. Schematic view of the magnet with the voltage tap locations is shown in Fig. 1. Further in the text or plots "top" coil stands for the racetrack magnet layer at the negative power lead and "bottom" coil – for the layer at the positive power lead.

9 strain gauges were installed on the aluminum skin for monitoring mechanical strain during the magnet construction and testing.

In addition to the standard set of the dewar sensors two additional resistive temperature devices (RTD) *Cernox #43235* and *#43233* sensors were mounted on top and bottom of the magnet body respectively.

Magnet was connected to the 30 kA top plate. 30 mOhm dump resistor was used in this test. Due to extremely small inductance of the magnet ~ 30 μH, the current ripple of the power supply should be kept at minimum using the well adjusted regulator. Current noise was within ±40 A at the magnet current of ~25 kA.

One spot heater was installed on outer turn of the bottom layer at the lead end. Heater firing unit (HFU) bank capacitance and voltage was set to 2.4 mF and 30 V respectively. Spot heater test was not performed due to lack of time. No protection heaters were installed on the magnet.

The initial quench detection threshold for the half-coil signal was set to 1.0 V (signals from the bottom layer formed the 1st half-coil signal, and signals from the top layer - the 2nd half-coil signal). After first few quenches in the superconducting lead section this threshold was reduced to 0.5 V.

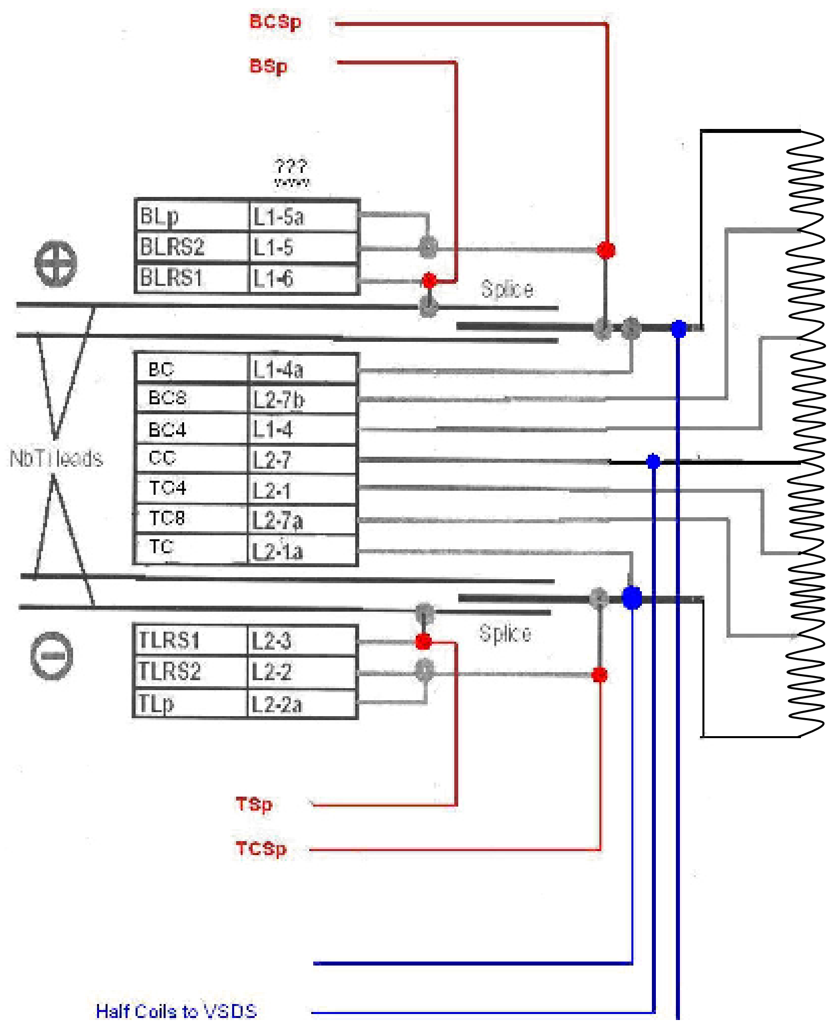

Figure 1. SR06 schematic view.

3. Quench History

The magnet cold test program at 4.5 K started with quench training at a ramp rate of 20 A/s. In the very first ramp copper leads tripped at a current of 19.1 kA. No resistive signal was observed in the splice or in the coil segments, so we increased the liquid helium flow in copper leads. In following ramp the first and only quench triggered by the top coil occurred at ~ 24.3 kA. All remaining quenches in coil segments were detected in the bottom layer.

Few quenches in the beginning developed in the superconducting (SC) lead section, specifically between the soldered joint at the negative copper power lead underneath the top plate and the NbTi splice segment. We increased the liquid helium level up to 26-27 cm (with the maximum level of 32 cm), but in ramp #5 when current reached a level of 27.5 kA, one of the PEI power supply modules (#5) developed an arc across phases in the circuit breaker.

SR06 test was suspended for almost 10 days from March 21 to March 31 and the magnet was idle in the dewar all this time and temperature level in dewar was maintained not to exceed 50 K (see Fig. 2).

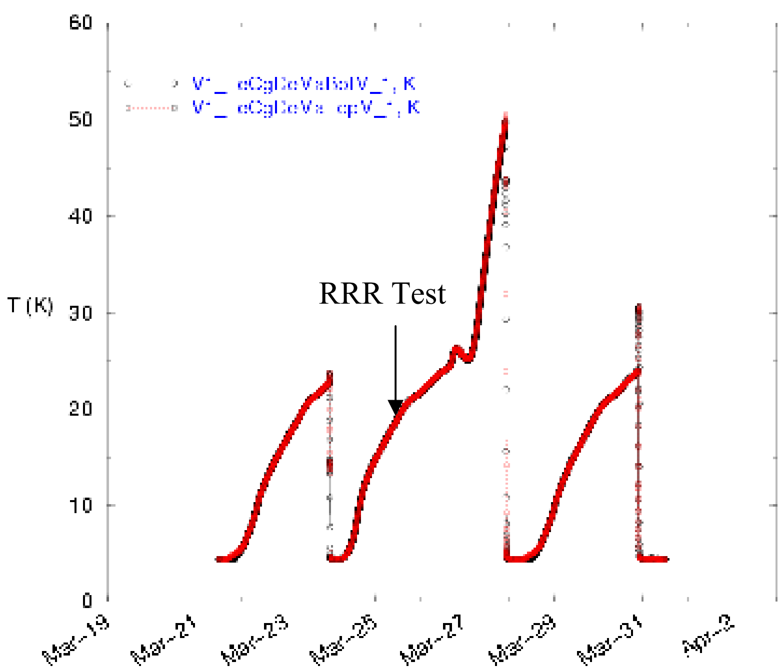

Figure 2. VMTF dewar temperature change at top and bottom of the SR06 magnet during the power supply recovery from March 21 to March 31.

The cold test was resumed at 4.5 K on March 31st and following quenches confirmed that the SC lead quenches could be avoided if the liquid helium level is increased in the dewar. Full quench history of the SR06 magnet test is presented in Fig. 3.

At 4.5 K, in ramp #7 the magnet reached a current of ~28 kA. But the magnet performance was unstable, quench currents varied in a wide range from almost the power supply limit (~ 29 kA) to much lower currents.

Next we started the ramp rate dependence study. Results of this study at both 4.5 K and 2.2 K temperatures are summarized in Section 4. Quenches at high ramp rates, 200 A/s and more, usually developed in both layers, but we always quote one of the layers, where the resistive signal starts earlier and is stronger than the signal from the another layer, as an origin of the quench development.

Test at 2.2 K showed rather erratic quench performance. In fact, quench currents at 2.2 K were even lower than quench currents at 4.5 K. Since we had limited time left for the test before the scheduled shutdown of the refrigerator plant, it was decided to skip all remaining items in the run plan and do again a ramp rate study at 4.5 K and 2.2 K.

The highest quench current achieved was 28.6 kA at 4.5 K (ramp # 36 at a 10 A/s ramp rate) and 26.6 kA at 2.2 K (ramp # 27 at a 20 A/s ramp rate). The complete quench history is presented in Tables 2 and 3.

Many quenches in this test were triggered by the SC lead signals in the analog or digital quench detection system (AQD or DQD). Quench data analysis confirmed that these quenches mostly developed in coils, but the SC lead signal was approaching the quench detection threshold (25 mV) earlier than the half-coil or whole-coil signals. We increased the threshold on the AQD and DQD SC lead signals from 25 mV to 35 mV after ramp #12, but still several quenches were detected by the SC lead signals (see Table 2).

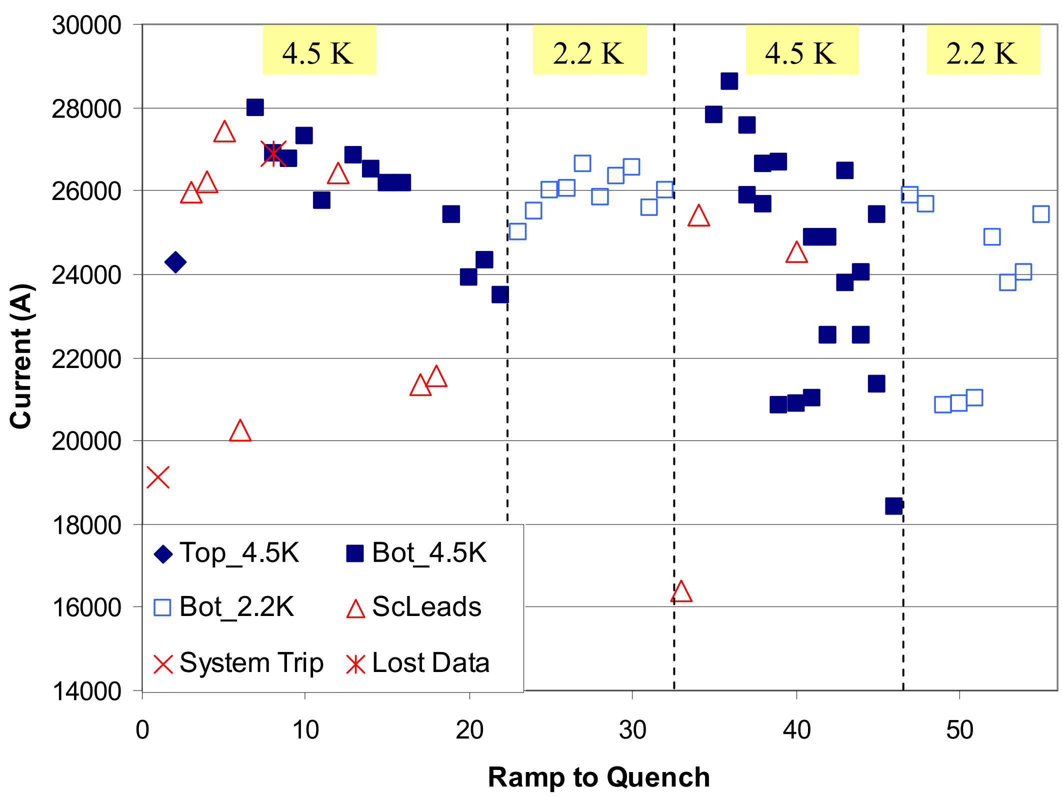

Figure 3. SR06 quench history.

SR06 magnet did not reach short sample limit and turned out to be unstable at 2.2 K. Another small racetrack magnet SR03 made of the similar Nb_3Sn RRP cable but with different configuration reached its short sample limits (~27.2 kA) at 4.5 K [3]. The test results of SR03 and SR06 magnets are compared in Table 1. Inconsistency in performance of SR06 magnet may be related to the cable damage during Rutherford cabling process or during the magnet production process. Cable in SR06, as well as in SR03 was with a keystone angle, which means that the relative arrangement of the narrow and thick edges of the cable in the magnet median plane, where the magnetic field is highest, could be an issue. In case of SR06 the cable of the bottom layer has its narrow edge at the median plane and as it was already mentioned above, most quenches developed in the bottom layer. From several pictures of the cable cross section we know that usually the narrow edges are much more damaged than the thick edges of the cable during the key-stoned cabling process.

Table 1. Comparison of data for SR03 and SR06 Magnets.

Magnet	Strand, No. of strands	No. of turns, Cross-section	Max. Current	Max. B	Stability	Problems
SR03	Nb_3Sn (108/127), RRP, 27 strands	13 Keystone	27.2 kA, 4.5K 28.1 kA, 2.2K	10.9 T 11.9 T	Stable	Training
SR06	Nb_3Sn (114/127), RRP, 27 strands	12 Keystone	28.6 kA, 4.5 K 26.6.kA, 2.2 K	10.3 T 9.7 T	Erratic operation	Training

Detailed inspection of the SC leads was performed after the test when the SR06 assembly was lifted from the VMTF. Main goal of this inspection was to understand reasons for the several trips in the SC lead section at the beginning of test. Suggestions were made for better routing and supporting of the SC leads. Summary of the SC lead inspection is presented in Appendix II.

Table 2. SR06 Quench History with comments

File	#	I (A)	dI/dt (A/sec)	t_{quench}	MIITs	QDC	Ave Temp	Comments
sr06.Quench.080318170447.819		1000	20	0.0004	0.08	WcoilGnd	4.438	manual trip at 1000A; 4.4K. LL=21.□
sr06.Quench.080318175603.628		1000	20	-0.0036	0.08	GndRef	4.440	another trip at 1000A. 4.44K
sr06.Quench.080318183338.888	**1**	19243	20	0.0000	0.75	WcoilIdot	4.457	quench at 19115.9A with ramp rate 20A/s. 4.5K.
sr06.Quench.080318190330.767	**2**	24342	20	-0.0039	3.31	WcoilGnd	4.471	quench at 24303A, ramp rate 20A/s. 4.44K.
sr06.Quench.080321125409.559	**3**	26023	20	-0.0161	11.96	SlWcoil	4.477	quench at 25958.5A, ramp rate 20A/s, 4.5Kto
sr06.Quench.080321151524.005	**4**	26285	20	-0.0287	20.94	SlWcoil	4.475	DQD_leads tripped at 26203A, 20A/s (30A/s upto 10kA), 4.45K
sr06.Quench.080321164331.438	**5**	27374	20	-0.0007	1.66	SlWcoil	4.483	quench at 27438A, 20A/s [50A/s upto 10kA, 30A/s upto 18kA], 4.44K
sr06.Quench.080331142009.957		1000	20	0.0003	0.08	WcoilGnd	4.435	DQD-coil induced trip at 1000A. 4.5K
sr06.Quench.080331150252.240	**6**	20357	20	-0.0006	1.06	WcoilGnd	4.453	AQD leads trip at 20250A, 20A/s (30A/s to 20kA) 4.45K
sr06.Quench.080331155242.582	**7**	27978	20	-0.0032	3.74	WcoilGnd	4.484	quench in SC leads at 28103.1A, 4.5K, LL=26.5 (setting)
sr06.Quench.080331164140.809	**8**	26912	20	----	----	----	----	**[Quench data lost - DAQ problem]**
sr06.Quench.080331180949.382	**9**	26761	20	-0.0028	3.13	WcoilGnd	4.481	quench at 26704A, 20A/s (50A/s to 16kA and 30A/s to 20kA), 4.44K.
sr06.Quench.080331193342.897	**10**	27302	20	-0.0029	3.31	HcoilHcoil	4.485	Quench at 27294.4A with ramp rate 20A/s (50A/s to 16kA and 30A/s to 20kA). 4.5K
sr06.Quench.080401105806.563	**11**	25749	20	-0.0046	4.07	WcoilGnd	4.467	quench at 25606.3A, ramp rate 20A/s (50A/s to 16kA, 30A/s to 20kA). 4.44K
sr06.Quench.080401124351.795	**12**	26454	20	0.0000	1.16	WcoilGnd	4.473	quench at 26447.2A with ramp arte of 20A/s (50A/s to 10kA, 30A/s to 18kA) 4.44K.
sr06.Quench.080401144150.388	**13**	26982	20	-0.0036	3.72	WcoilGnd	4.473	quench at 26862.1A with ramp rate of 20A/s (50A/s to 10kA, 30A/s to 18kA). 4.44K.
sr06.Quench.080401161222.750	**14**	26610	20	-0.0046	4.37	HcoilHcoil	4.471	quench at 26521.3A, 20A/s (50A/s to 15kA, 30A/s to 19kA), 4.44K.
sr06.Quench.080401165246.428	**15**	26319	50	-0.0043	4.04	WcoilGnd	4.457	quench at 26182.7A with ramp rate 50A/s. 4.44K
sr06.Quench.080401172637.690	**16**	26297	100	-0.0095	7.68	HcoilHcoil	4.441	quench at 26183.6A with ramp rate of 100A/s. 4.44K
sr06.Quench.080401175042.934	**17**	21384	150	-0.0062	3.68	SlWcoil	4.436	quench at 21367A, ramp rate=150A/s, 4.44K
sr06.Quench.080401181326.776	**18**	21560	200	-0.0029	2.18	SlWcoil	4.434	quench at 21548.3A, ramp rate 200A/s, 4.43K
sr06.Quench.080401183347.569	**19**	25561	268	-0.0046	4.02	WcoilGnd	4.435	quench at 25421.2A, reamp rate 300A/s, 4.44K

sr06.Quench.080401185008.513	**20**	24027	268	-0.0045	3.52	WcoilGnd	4.433	quench at 23912.6A, ramp rate 400A/s, 4.44K
sr06.Quench.080401191254.085	**21**	24398	315	-0.0070	5.18	HcoilHcoil	4.436	quench at 24333A, ramp rate 500A/s, 4.4K
sr06.Quench.080401193413.693	**22**	23749	200	-0.0073	5.44	WcoilGnd	4.440	quench at 23481.5A, ramp rate 200A/s, 4.44K
sr06.Quench.080402113457.852	**23**	25020	20	-0.0203	13.70	WcoilGnd	2.163	quench at 24764.4A with ramp rate 20A/s (50A/s to 15kA, 30A/s to 19kA), 2.16K
sr06.Quench.080402122330.391	**24**	25496	20	-0.0197	13.78	WcoilGnd	2.163	quench at 25287.6A, ramp rate 20A/s (50A/s to 16kA, 30A/s to 20kA).
sr06.Quench.080402132530.747	**25**	26030	20	-0.0090	7.18	WcoilIdot	2.163	quench at 25878.9A, 20A/s (50A/s to 16kA, 30A/s to 20kA), 2.16K.
sr06.Quench.080402144056.138	**26**	26062	20	-0.0210	15.34	HcoilHcoil	2.164	quench at 25882A, 20A/s (50A/s to 16kA, 30A/s to 20kA), 2.16K
sr06.Quench.080402153812.411	**27**	26636	20	-0.0069	5.94	WcoilGnd	2.164	quench at 26560A, ramp rate 20A/s (50A/s to 16kA, 30A/s to 20kA)
sr06.Quench.080402162931.688	**28**	25828	20	-0.0211	15.08	HcoilHcoil	2.163	quench at 25643A, 20A/s (50A/s to 16kA, 30A/s to 20kA), 2.16K
sr06.Quench.080402172117.177	**29**	26342	20	-0.0080	6.62	HcoilHcoil	2.163	quench at 26154.6A, 20A/s (50A/s to 16kA, 30A/s to 19kA), 2.16K
sr06.Quench.080402181808.499	**30**	26574	20	-0.0059	5.25	WcoilGnd	2.164	quench at 26376.6A, 20A/s (50A/s to 17kA, 30A/s to 20kA), 2.16K
sr06.Quench.080402191259.744	**31**	25600	20	-0.0076	5.98	WcoilIdot	2.164	quench at 25372.4A, 20A/s (50A/s to 17kA, 30A/s to 20kA), 2.16K
sr06.Quench.080402200226.556	**32**	25991	20	-0.0203	14.71	HcoilHcoil	2.164	quench at 25806.3A with 20 A/s (50A/s to 17kA, 30A/s to 20kA), 2.16K
sr06.Quench.080404081618.125	**33**	15601	30	0.0001	0.63	WcoilIdot	4.207	Trip in leads at 16380A. 30A/s (50A/s to 16kA), T=4.2K
sr06.Quench.080404095837.898	**34**	25495	20	-0.0295	20.26	SlWcoil	4.255	quench at 25436.2A, 20A/s (50A/s to 16kA, 30A/s to 19kA), 4.22K
sr06.Quench.080404104842.993	**35**	27881	20	-0.0029	3.46	WcoilGnd	4.283	quench at 27807.9A, 20A/s (50A/s to 16kA, 30A/s to 20kA), 4.26K.
sr06.Quench.080404115458.130	**36**	28611	10	-0.0029	3.60	SlWcoil	4.327	quench at 28611A, 10A/s (50A/s to 16kA, 30A/s to 20kA), 4.32K.
sr06.Quench.080404130647.250	**37**	27638	20	-0.0038	4.01	WcoilGnd	4.357	quench at 27492A with ramp rate 20A/s (50A/s to 17kA, 30A/s to 20kA). 4.33K
sr06.Quench.080404140643.148	**38**	26634	20	-0.0046	4.32	WcoilGnd	4.391	ramp 38, 4.45K, 50A/s to 16kA, 30A/s to 20kA, 20A/s to quench
sr06.Quench.080404145411.035	**39**	26717	150	-0.0036	3.67	WcoilGnd	4.405	quench at 26590.1A with ramp rate of 150A/s. 4.4K.
sr06.Quench.080404152156.088	**40**	24557	200	-0.0283	18.00	SlWcoil	4.403	quench at 24493.5A with ramp rate 200A/s. 4.4K.
sr06.Quench.080404155245.640	**41**	24890	200	-0.0085	6.74	WcoilIdot	4.416	quench at 24635A with 200A/s ramp rate
sr06.Quench.080404161700.964	**42**	22548	442	-0.0066	4.53	WcoilGnd	4.410	quench at 22259.1A, ramp rate 700A/s, 4.4Ko
sr06.Quench.080404164546.270	**43**	26480	100	-0.0046	4.32	WcoilGnd	4.424	quench at 26318.2A at 100A/s, 4.4K

sr06.Quench.080404170409.239	**44**	22428	448	-0.2694	136.86	WcoilGnd	4.416	quench at ~22kA, ramp rate requested 900A/s but due to low acceleration we did not get 900A/s.
sr06.Quench.080404172833.563	**45**	21358	662	-0.0091	5.28	WcoilGnd	4.413	quench at 21037A with requested 700A/s ramp rate, acceleration 100A/s0
sr06.Quench.080404174526.188	**46**	18400	851	-0.0140	5.62	WcoilGnd	4.409	quench at 18132A with requested ramp rate of 850A/s. 4.4Kœ
sr06.Quench.080405101813.433	**47**	25872	9	-0.0220	15.69	HcoilHcoil	2.148	quench at ~25.6kA with ramp rate 10A/s (50A/s to 16kA, 30A/s to 20kA), 2.14K.
sr06.Quench.080405111826.493	**48**	25682	16	-0.0084	6.47	WcoilIdot	2.150	quench at ~25.4kA with ramp rate of 20A/s (50A/s to 17kA, 30A/s to 20kA), 2.15K
sr06.Quench.080405115521.401	**49**	20858	850	-0.0253	12.11	WcoilGnd	2.151	quench at 20577.8A with ramp rate of 850A/s
sr06.Quench.080405121354.279	**50**	20853	700	-0.0256	12.20	WcoilIdot	2.154	quench at ~20.6kA with ramp rate 700A/s, 2.15K
sr06.Quench.080405122827.229	**51**	21019	450	-0.0265	12.76	WcoilIdot	2.150	quench at ~20.7kA with ramp rate of 450A/s. 2.15K
sr06.Quench.080405125513.470	**52**	24865	300	-0.0097	6.94	WcoilIdot	2.150	quench at ~24.5kA with ramp rate of 300A/s. 2.15K
sr06.Quench.080405131359.681	**53**	23767	200	-0.0970	55.66	HcoilHcoil	2.151	quench at ~23.5kA with ramp rate of 200A/s, 2.15K
sr06.Quench.080405134109.232	**54**	24040	150	-0.0127	8.17	WcoilIdot	2.151	quench at ~23.7kA with ramp rate of 150A/s. 2.15K
sr06.Quench.080405140922.677	**55**	25430	100	-0.0062	5.02	WcoilGnd	2.150	quench at ~25.2kA with ramp rate of 100A/s. 2.15K

Table 3. SR06 Quench History with parameters for the first two quenching segments

File	**#**	**I (A)**	**dI/dt (A/sec)**	**t_{quench}**	**MIITs**	**1st VTseg**	**t_{rise}**	**2nd VTseg**	**t_{rise}**	**T (K) Bottom**	**T (K) Top**
sr06.Quench.080318170447.819		1000	20	0.0004	0.08					4.438	4.438
sr06.Quench.080318175603.628		1000	20	-0.0036	0.08					4.441	4.440
sr06.Quench.080318183338.888	**1**	19243	20	0.0000	0.75	Copper Leads				4.456	4.459
sr06.Quench.080318190330.767	**2**	24342	20	-0.0039	3.31	CC-TC4	-0.0043	TC4-TC8	-0.0031	4.468	4.475
sr06.Quench.080321125409.559	**3**	26023	20	-0.0161	11.96	ScLeads				4.476	4.478
sr06.Quench.080321151524.005	**4**	26285	20	-0.0287	20.94	ScLeads				4.474	4.476
sr06.Quench.080321164331.438	**5**	27374	20	-0.0007	1.66	ScLeads				4.481	4.486
sr06.Quench.080331142009.957		1000	20	0.0003	0.08					4.436	4.435

sr06.Quench.080331150252.240	**6**	20357	20	-0.0006	1.06	ScLeads				4.449	4.457
sr06.Quench.080331155242.582	**7**	27978	20	-0.0032	3.74	BC-BC8	-0.0038	BC8-BC4	-0.0036	4.481	4.486
sr06.Quench.080331164140.809	**8**	26912	20	----	----	------------	----	------------	----	----	----
sr06.Quench.080331180949.382	**9**	26761	20	-0.0028	3.13	BC-BC8	-0.0035	BC8-BC4	-0.0035	4.481	4.482
sr06.Quench.080331193342.897	**10**	27302	20	-0.0029	3.31	BC8-BC4	-0.0035	BC-BC8	-0.0035	4.482	4.488
sr06.Quench.080401105806.563	**11**	25749	20	-0.0046	4.07	BC8_BC4	-0.0035	BC4_CC	-0.0032	4.465	4.469
sr06.Quench.080401124351.795	**12**	26454	20	0.0000	1.16	ScLeads				4.472	4.474
sr06.Quench.080401144150.388	**13**	26982	20	-0.0036	3.72	BC8-BC4	-0.0039	BC-BC8	-0.0039	4.471	4.476
sr06.Quench.080401161222.750	**14**	26610	20	-0.0046	4.37	BC8-BC4	-0.0043	BC4-CC	-0.0043	4.471	4.472
sr06.Quench.080401165246.428	**15**	26319	50	-0.0043	4.04	BC8-BC4	-0.0046	BC-BC8	-0.0046	4.455	4.459
sr06.Quench.080401172637.690	**16**	26297	100	-0.0095	7.68	BC4_CC	-0.0032	BC8_BC4	-0.0032	4.441	4.441
sr06.Quench.080401175042.934	**17**	21384	150	-0.0062	3.68	ScLeads				4.436	4.436
sr06.Quench.080401181326.776	**18**	21560	200	-0.0029	2.18	ScLeads				4.435	4.433
sr06.Quench.080401183347.569	**19**	25561	268	-0.0046	4.02	BC8-BC4	-0.0053	BC-BC8	-0.0051	4.435	4.434
sr06.Quench.080401185008.513	**20**	24027	268	-0.0045	3.52	BC8_BC4	-0.0032	BC_BC8	-0.0029	4.433	4.433
sr06.Quench.080401191254.085	**21**	24398	315	-0.0070	5.18	BC8_BC4	-0.0038	BC_BC8	-0.0036	4.436	4.436
sr06.Quench.080401193413.693	**22**	23749	200	-0.0073	5.44	BC8_BC4	-0.0063	TC4_TC8	-0.0062	4.441	4.439
sr06.Quench.080402113457.852	**23**	25020	20	-0.0203	13.70	BC8_BC4	-0.0070	TC4_TC8	-0.0066	2.164	2.163
sr06.Quench.080402122330.391	**24**	25496	20	-0.0197	13.78	BC8_BC4	-0.0055	TC4_TC8	-0.0053	2.164	2.163
sr06.Quench.080402132530.747	**25**	26030	20	-0.0090	7.18	BC8_BC4	-0.0053	TC4_TC8	-0.0050	2.164	2.163
sr06.Quench.080402144056.138	**26**	26062	20	-0.0210	15.34	BC4_CC	-0.0053	BC8_BC4	-0.0053	2.165	2.163
sr06.Quench.080402153812.411	**27**	26636	20	-0.0069	5.94	BC8_BC4	-0.0049	TC4_TC8	-0.0048	2.165	2.163
sr06.Quench.080402162931.688	**28**	25828	20	-0.0211	15.08	BC4_CC	-0.0053	CC_TC4	-0.0053	2.164	2.163
sr06.Quench.080402172117.177	**29**	26342	20	-0.0080	6.62	BC8_BC4	-0.0053	BC4_CC	-0.0052	2.164	2.163
sr06.Quench.080402181808.499	**30**	26574	20	-0.0059	5.25	BC8_BC4	-0.0048	BC_BC8	-0.0045	2.165	2.163
sr06.Quench.080402191259.744	**31**	25600	20	-0.0076	5.98	BC8_BC4	-0.0059	CC_TC4	-0.0053	2.165	2.163
sr06.Quench.080402200226.556	**32**	25991	20	-0.0203	14.71	BC8_BC4	-0.0055	CC_TC4	-0.0049	2.164	2.164
sr06.Quench.080404081618.125	**33**	15601	30	0.0001	0.63	ScLeads				4.207	4.207
sr06.Quench.080404095837.898	**34**	25495	20	-0.0295	20.26	ScLeads				4.246	4.264
sr06.Quench.080404104842.993	**35**	27881	20	-0.0029	3.46	BC8_BC4	-0.0034	BC4_CC	-0.0034	4.265	4.300
sr06.Quench.080404115458.130	**36**	28611	10	-0.0029	3.60	BC8_BC4	-0.0036	BC4_CC	-0.0036	4.306	4.349
sr06.Quench.080404130647.250	**37**	27638	20	-0.0038	4.01	BC8_BC4	-0.0042	BC4_CC	-0.0039	4.337	4.376
sr06.Quench.080404140643.148	**38**	26634	20	-0.0046	4.32	BC8_BC4	-0.0036	BC4_CC	-0.0034	4.370	4.413
sr06.Quench.080404145411.035	**39**	26717	150	-0.0036	3.67	BC8_BC4	-0.004	BC_BC8	-0.0039	4.385	4.425
sr06.Quench.080404152156.088	**40**	24557	200	-0.0283	18.00	ScLeads				4.391	4.414
sr06.Quench.080404155245.640	**41**	24890	200	-0.0085	6.74	BC_BC8	-0.0055	BC8_BC4	-0.0055	4.412	4.419
sr06.Quench.080404161700.964	**42**	22548	442	-0.0066	4.53	BC8_BC4	-0.0057	TC4_TC8	-0.0056	4.411	4.410

sr06.Quench.080404164546.270	**43**	26480	100	-0.0046	4.32	BC8_BC4	-0.0036	BC_BC8	-0.0035	4.424	4.423
sr06.Quench.080404170409.239	**44**	22428	448	-0.2694	136.86	BC8_BC4	-0.0059	BC4_CC	-0.0055	4.416	4.415
sr06.Quench.080404172833.563	**45**	21358	662	-0.0091	5.28	BC4_CC	-0.0080	BC8_BC4	-0.0078	4.414	4.413
sr06.Quench.080404174526.188	**46**	18400	851	-0.0140	5.62	BC8_BC4	-0.0123	TC4_TC8	-0.0123	4.409	4.408
sr06.Quench.080405101813.433	**47**	25872	9	-0.0220	15.69	BC4_CC	-0.0063	BC8_BC4	-0.0063	2.149	2.148
sr06.Quench.080405111826.493	**48**	25682	16	-0.0084	6.47	BC8_BC4	-0.0063	CC_TC4	-0.0060	2.151	2.150
sr06.Quench.080405115521.401	**49**	20858	850	-0.0253	12.11	BC8_BC4	-0.0076	BC4_CC	-0.0074	2.151	2.150
sr06.Quench.080405121354.279	**50**	20853	700	-0.0256	12.20	BC_BC8	-0.0108	BC8_BC4	-0.0095	2.154	2.153
sr06.Quench.080405122827.229	**51**	21019	450	-0.0265	12.76	BC8_BC4	-0.0090	BC_BC8	-0.0087	2.150	2.149
sr06.Quench.080405125513.470	**52**	24865	300	-0.0097	6.94	BC8_BC	-0.0077	BC8_BC4	-0.0073	2.151	2.150
sr06.Quench.080405131359.681	**53**	23767	200	-0.0970	55.66	BC_BC8	-0.0107	BC8_BC4	-0.010	2.152	2.151
sr06.Quench.080405134109.232	**54**	24040	150	-0.0127	8.17	BC8_BC4	-0.0095	BC_BC8	-0.0092	2.152	2.151
sr06.Quench.080405140922.677	**55**	25430	100	-0.0062	5.02	BC8_BC4	-0.0056	BC_BC8	-0.0052	2.151	2.150

4. Ramp Rate Dependence

Several quenches were performed for the ramp rate dependence study at 4.5 K and 2.2 K. A plot summarizing all ramp rate quenches is shown in Fig. 4.

At 4.5 K, the ramp rate study was performed in two steps: at the beginning of the cold test and then at the very end of test – after the quench training at 2.2 K.

SR06 ramp rate dependence is rather smooth, without a sharp drop in the quench current at ramp rates up to 850 A/s. Training quenches at a ramp rate of 20 A/s also are shown in Fig. 4.

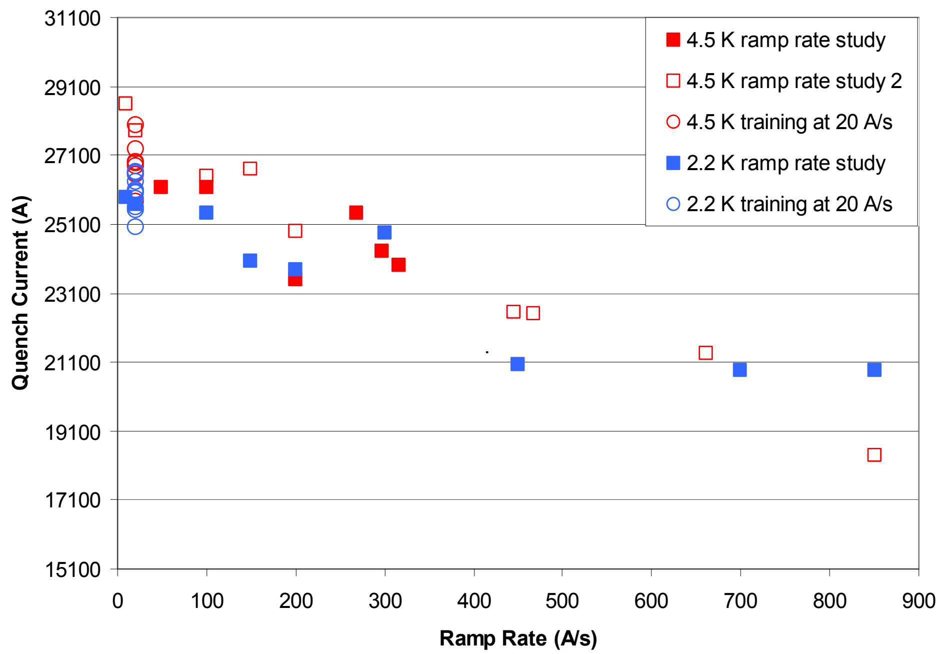

Figure 4. Ramp rate study at 4.5 K and 2.2 K.

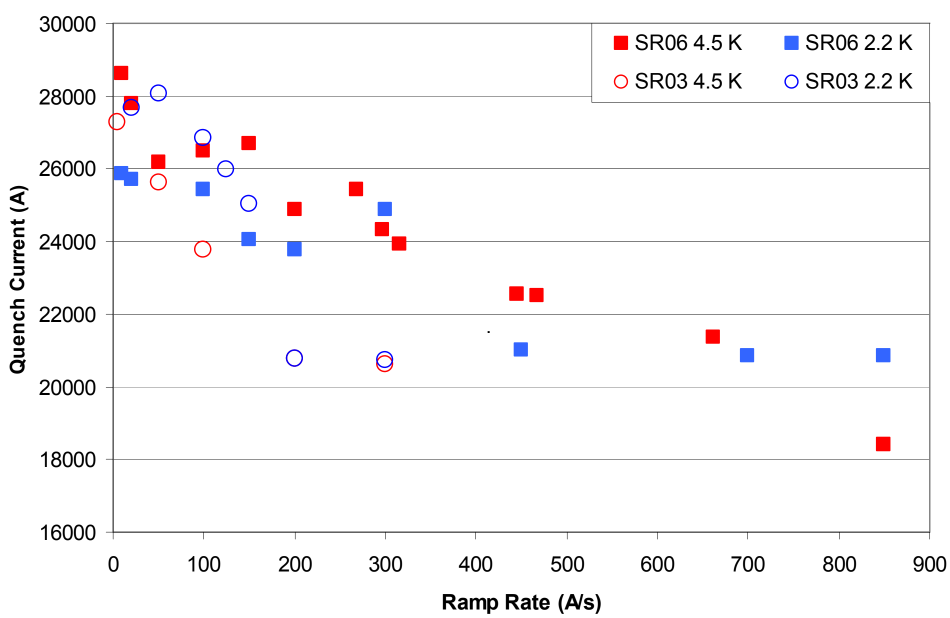

Figure 5. SR03 and SR06 ramp rate dependences at 4.5 K and 2.2 K.

Ramp rate dependence for SR03 and SR06 magnets are compared in Fig. 5. We see a clear difference in quench performance of SR03 and SR06, especially at 2.2 K.

5. Measurement of the Residual Resistivity Ratio (RRR)

Estimates of RRR in SR06 coil segments have been made using data captured during the power supply maintenance work while the magnet was idle in the VMTF dewar almost 10 days (see Fig. 2). Transition from superconducting to normal occurred at late evening of March 25th and data captured at ~ 9 pm was used for the cold voltage measurements. Temperature of the magnet was 17.8 K when the transition occurred. "Warm" voltage measurements at a room temperature were captured on March 12 when preliminary data checkout was performed before the test.

Coil voltages across "configurable" voltage tap segments were monitored by the *Pentek* data loggers, while a current of alternating polarity, +/- 10.0 ± 0.4 A, was put through the magnet. For both warm (~ 300 K) and cold (~ 18 K) measurements we used the RRR amplifier gains (x1000) for the voltage tap segments to maximize the signal levels.

Data for all segments are shown in Table 4 and the results are graphed in Fig. 6.

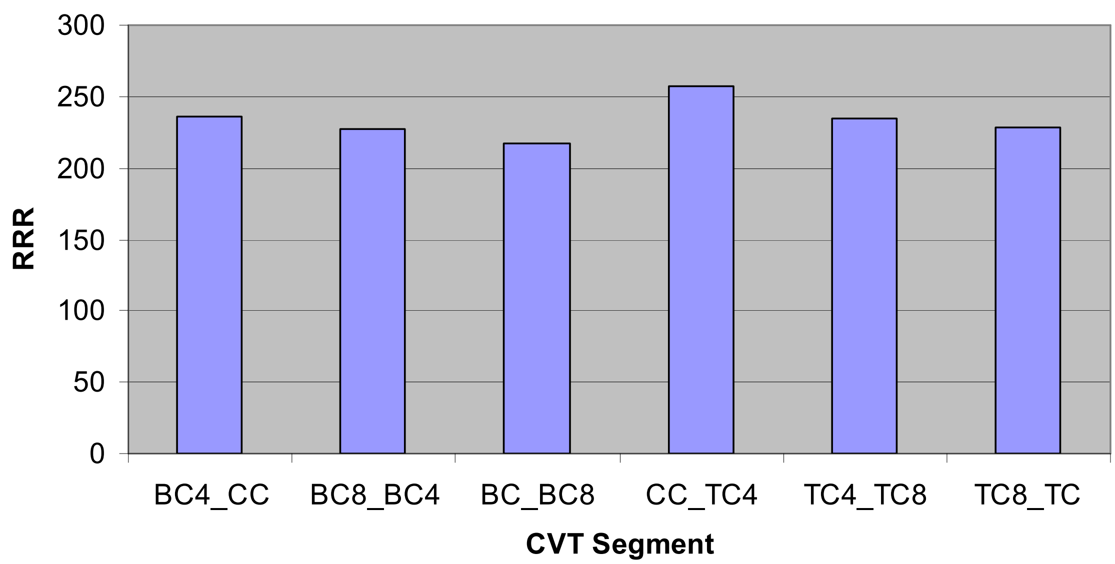

Figure 6. RRR measurements for the configurable voltage tap (CVT) segments.

Table 4. RRR data for all the CVT segments in SR06. ΔI=19.8 A at 18 K and ΔI=14.2 A at 300 K

Segment	Δ (V+ - V-)	R (cold)		Δ (V+ - V-)	R (warm)	RRR
BC4_CC	0.0354	0.0017862		6.1158	0.4213144	235.9
BC8_BC4	0.0409	0.0020637		6.8198	0.4698126	227.7
BC_BC8	0.052094	0.0026285		8.2767	0.5701777	216.9
CC_TC4	0.0311	0.0015692		5.8584	0.4035823	257.2
TC4_TC8	0.0399	0.0020132		6.873	0.4734775	235.2
TC8_TC	0.0493	0.0024875		8.2687	0.5696266	229.0

6. Quench Locations

All quenches both at 4.5 K and 2.2 K were detected in the bottom layer except one - the quench #2 at 4.5 K, which developed in the top layer. As it was mentioned in Section 3 the relative arrangement of the narrow and thick edges of the cable in the magnet median plane, where the magnetic field is highest, could explain why most of the quenches developed in the bottom layer. The bottom layer cable has its narrow edge at the median plane and usually the narrow edges are much more damaged than the thick edges of the cable during the key-stoned cabling process.

One should mention that all quenches at high ramp rates (200 A/s and more) and many quenches at low ramp rates too developed in both layers, but in most cases quench was triggered by the signal from the bottom layer. The typical quench pattern for quench #36 at a ramp rate of 10 A/s is shown in Fig. 7.

Most quenches in the bottom layer originated from the middle segment of the coil ***BC8-BC4***. One single quench triggered by the top layer signal occurred in the central segment ***CC-TC4*** (see voltage tap locations in Fig. 1).

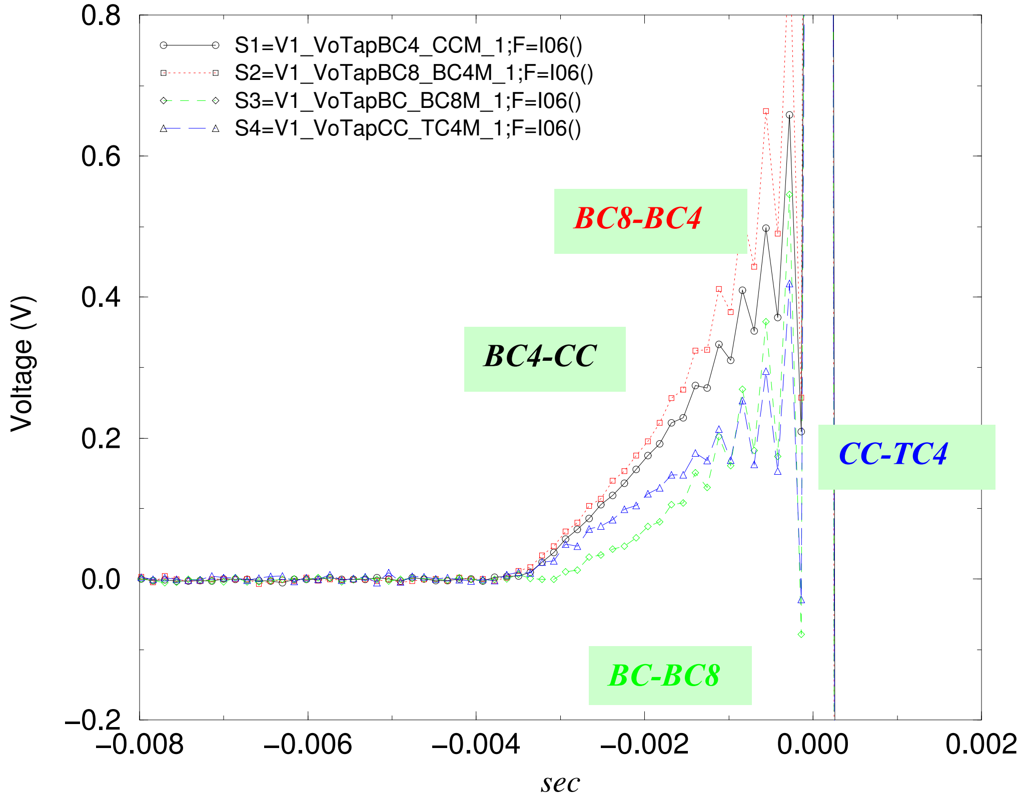

Figure 7. Quench scan data at a ramp rate of 10 A/s and 4.5 K operation.

7. Conclusion

Small racetrack magnet SR06 with Nb_3Sn coils made of 1-mm diameter 114/127 RRP strand was fabricated and tested at Fermilab.

The highest quench current achieved was 28,611 A at 4.5 K and 26,636 A at 2.2 K. Magnet exhibited unstable quench performance at both 4.5 K and 2.2 K, which may be related to the cable damage during Rutherford cabling process or during the magnet production process. The measured coil Residual Resistivity Ratio varied within 220-260 range.

Several quenches occurred in the SC lead section at the beginning of test. It was found that these lead quenches were avoided if the liquid helium level was increased significantly in the dewar.

SR06 run plan was not fully completed due to interruptions in test run related to the power supply problems, as well as due to the limited test time before the scheduled shutdown of the refrigerator plant.

References

[1] S. Hong et al., "Latest improvements of current carrying capability of niobium tin and its magnet applications", *IEEE Trans. on Appl. Supercond.,* vol.16, Issue 2, 2005, p.1146

[2] S. Feher et al., "SR03 Test Summary Report", TD-06-047, 02/20/06.

[3] E. Barzi et al., "Performance of Nb_3Sn RRP strands and Cables Based on a 108/127 Stack Design", *IEEE Trans. Appl. Supercond*., vol. 17, pp. 2718, June 2007.

Appendix I

Short sample test data

Short Sample Data of Strand

Small Racetrack SR06 Witnesses

SampleN	1	1	1	1
Teslatron	2	2	2	1
Probe	3	5	3	2
HeatT	SR06 witness	SR06 witness	SR06 witness	SR06 witness
Holder	SS	Ti	Ti	SS
Maker	OST	OST	OST	OST
Tech	RRP	RRP	RRP	RRP
Billet	9772-2	9772-2	9772-2	9772-2
Type	extracted from HFDB_070531_27_1_0	extracted from HFDB_070531_27_1_0	Round	Round
Diam	1	1	1	1
Splices	yes	yes	yes	yes
Stycast	no	yes	no	No
Cu %	50	50	50	50
DateOfTest	9/13/2007	9/14/2007	9/17/2007	9/17/2007

Field(T)	Iq(A)	Ic(A) Vt1	N Vt1	Ic(A) Vt2	N Vt2	Iq(A)	Ic(A) Vt1	N Vt1	Ic(A) Vt2	N Vt2	Iq(A)	Ic(A) Vt1	N Vt1	Ic(A) Vt2	N Vt2	Iq(A)	Ic(A) Vt1	N Vt1	Ic(A) Vt2	N Vt2
15																438	404	40	426	[34.02]
14	246	resistive		FLAT		645	638	[38.5]	628	[23.1]	581	526	32	526	30	544	517	47	[560.0]	
13	271	resistive		FLAT		808	806	[36.7]	799	[31.1]	732	670	30	669	29	670	649	[53.9]	V34 Flat	
12	298	resistive		FLAT		996	995	[49.1]	988	[30.7]	913	838	28	840	29	818	803	[56.9]	V34 Flat	
11						1020	PSL		PSL		1020	PSL		PSL		996	991	[52.1]	V34 Flat	
10						1020	PSL		PSL		1020	PSL		PSL		1212	[1217.0]	[65.5]	V34 Flat	
8	424	resistive		FLAT		1020	PSL		PSL		1020	PSL		PSL		1791	PSL		PSL	
6						1018	PSL		PSL		1015	PSL		PSL		1788	PSL		PSL	
4	664	resistive		FLAT		1015	PSL		PSL		1015	PSL		PSL		1788	PSL		PSL	
2	918	resistive		FLAT		1019	PSL		PSL		1019	PSL		PSL		1789	PSL		PSL	
0	1017[PSL]	resistive		FLAT		1016	PSL		PSL		1016	PSL		PSL		1787	PSL		PSL	
RRR		136		101			132					172					173			
Note	Bad Sample																			

Sweeping field (T)	I[A]	Bq[T]	dir	I[A]	Bq[T]	dir	I[A]	Bq[T]	dir	I[A]	Bq[T]	dir
	802	2.763	0-4T	1010	N.Q	0-4T	1010	N.Q	0-4T	1587	N.Q	0-4T
	700	3.713	0-4T	1010	N.Q	4T-0	1010	N.Q	4T-0	1587	N.Q	4T-0
	650	N.Q	0-4T							1756	N.Q	0-4T
	650	N.Q	4T-0							1756	N.Q	4T-0
										1785[psl]	N.Q	0-4T
										1785[psl]	N.Q	4T-0

N-values calculated using power law fit from Vc to 10Vc. N-value in red means that the voltage over which the fit was performed did not reach 10Vc (this means that uncertainty may be larger).
Ic in red shows extrapolated values

Appendix II

SR06 Superconducting Leads Inspection **by M. Tartaglia, 23 April 2008**

Introduction

During the quench testing of SR06 at 4.5K, there were few trips in the negative Sc Lead at currents as low as 16.4 kA, with voltage signals indicating possible motion that sometimes resulted in actual lead quenches.

Findings

Following the warm up to room temperature on 4/21/08 the SR06 assembly was lifted from VMTF and an inspection of the Superconducting Leads was made to look for conditions that might allow the observed quenches to develop there. We found that indeed, the negative superconducting lead was not well supported and could be moved fairly easily, while the positive lead was much more secure and difficult to move.

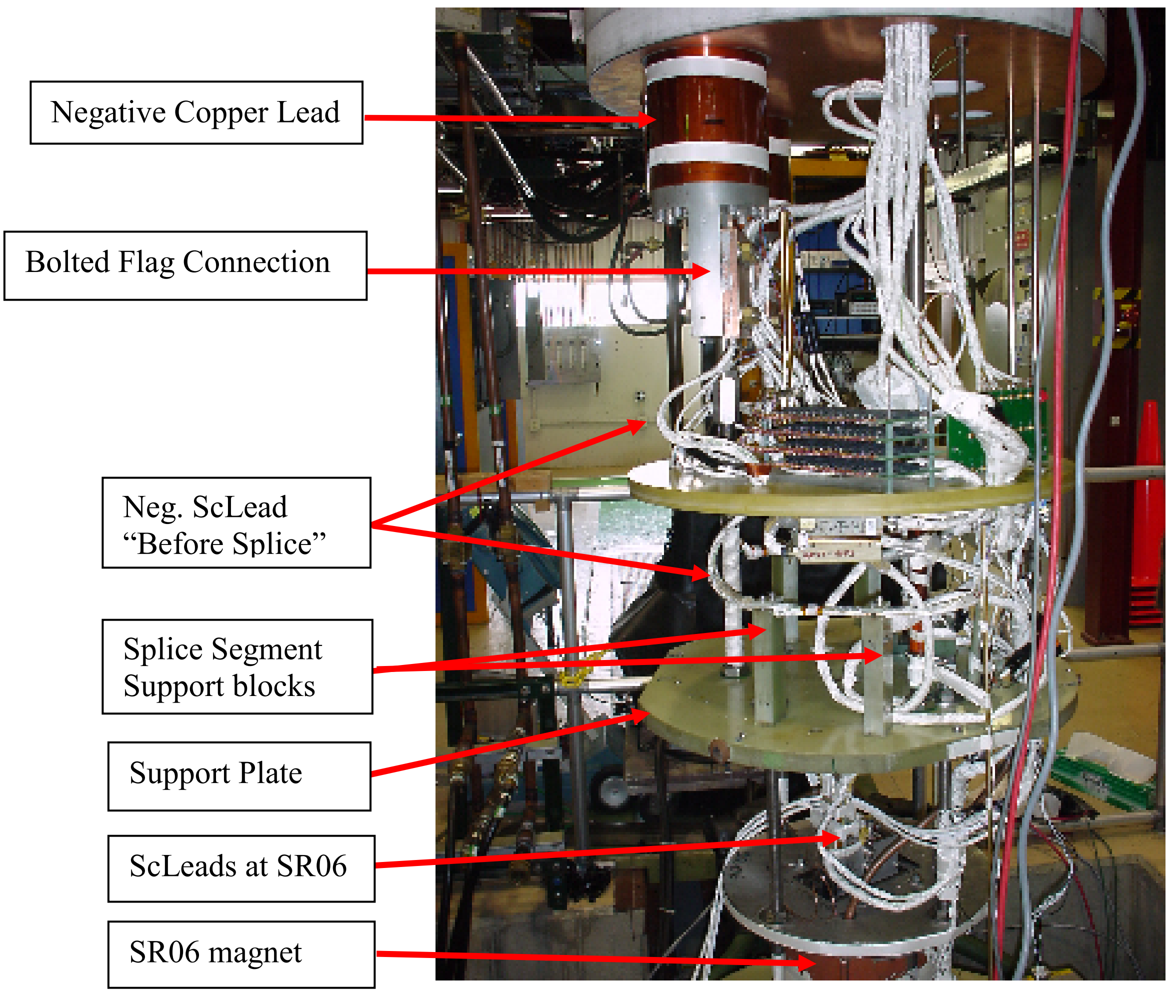

Figure 1. Overview of the 30kA Top plate and SR06 magnet assembly showing negative Sc Lead segments.

Figure 1 shows an overview of the assembly with various components identified. Figure 2 shows a detail view of the negative lead support post just beyond the splice support blocks: it is clearly tilted and does not provide a stable support (it was originally "under tension" from the lead itself, but clearly cool-down shrinkage and/or Lorentz forces allowed it to move). Figures 3 and 4 illustrate the arrangement of Sc Leads between the magnet and the splice block, and show a well secured positive lead, but unsecured negative lead. Figure 5 shows the magnet arranged on its mounting plate, with N2 shield and tubing. This arrangement is not ideal in terms of routing and supporting the Sc Leads – in particular, the question was raised ***whether it is possible to rotate the magnet 180 degrees, in order to directly take the Sc Leads through the support plate hole and route them to the nicely to the splice blocks above***. The magnet mounting plate defines the orientation: the flat edges must be aligned for connection to the top plate assembly. Also, the shield N2 tubing must remain in the present orientation, to connect to assembly fittings.

Photographs of the previous small racetrack magnets are not in the D&T Image archive (SR03 tested in February 2006, and SR04 tested in September 2006). However, the test reports and elog entries indicate that both of these magnet tests had many superconducting lead “trips”. Thus it seems likely that Sc Lead support was also a problem during those tests (though power supply regulation issues may have obscured recognition of this during the testing).

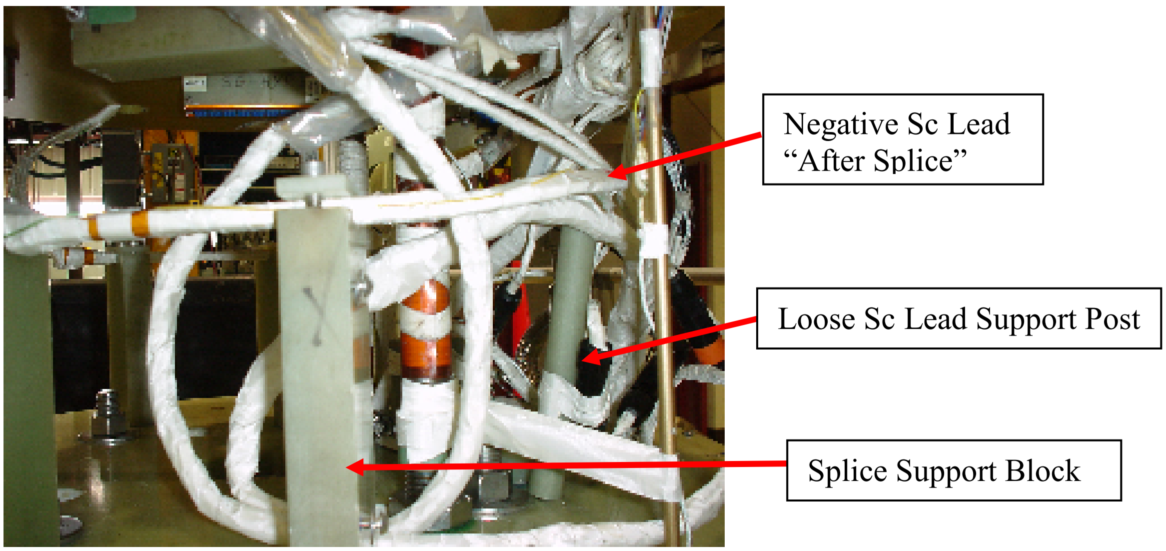

Figure 2. Negative Sc Lead beyond the splice support blocks, and lead support post which is tilted and not providing stable support.

Summary

The MSD magnet builders and T&I technicians need to agree upon a magnet mounting arrangement that allows a better routing, and standardize upon a method for securing the superconducting leads from small racetrack magnets to the splice block. In addition, there should be an inspection of the Sc leads (for all magnets) by an appropriate expert (to be defined) added to the checklist of mechanical preparation steps prior to the cool down.

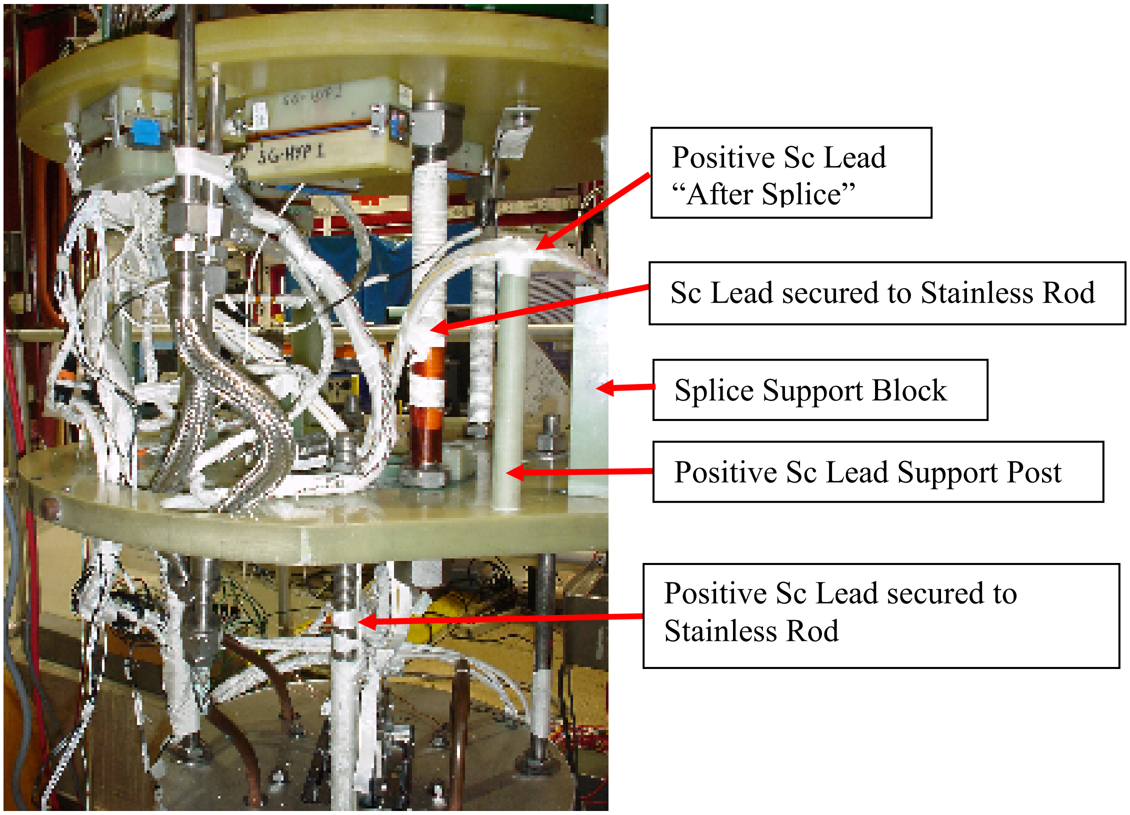

Figure 3. View of the positive Sc Lead support post, and points where positive Sc Lead is secured to stainless steel rods above and below the support plate.

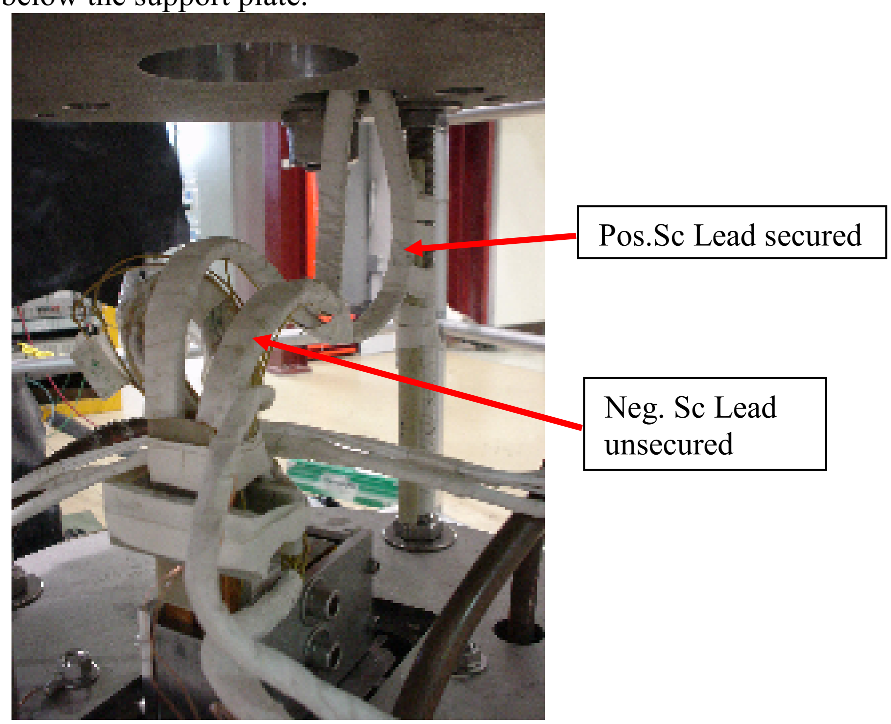

Figure 4. Sc Leads routed from SR06 through hole in support plate. Note that positive lead is well secured to Stainless Steel support rod (both below and above the plate), while the negative lead is essentially unsupported and is easily moved in this region.

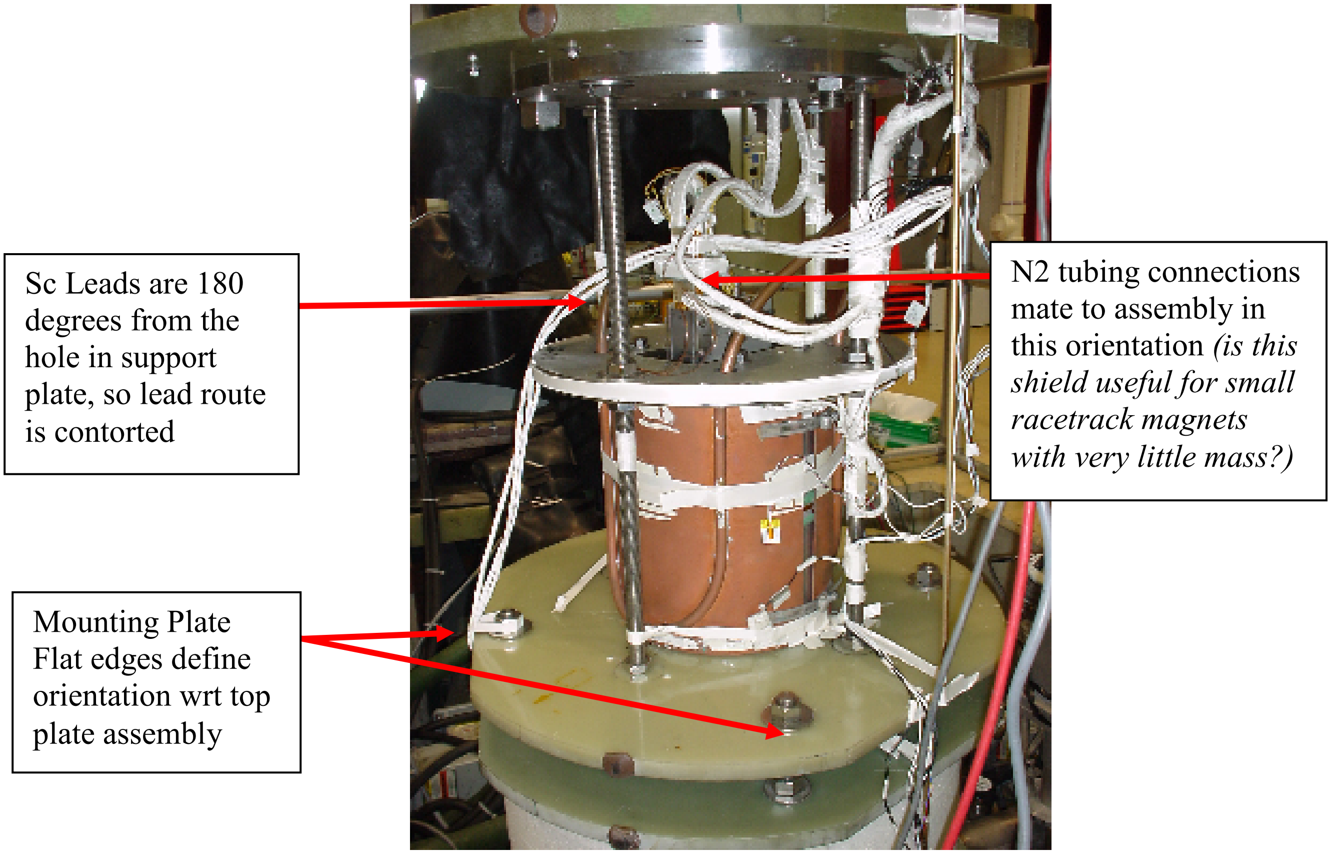

Figure 5. View of SR06 on mounting plate with copper (N2) heat exchanger.